THE JOURNAL OF

THE INSTITUTION OF PRODUCTION ENGINEERS

Vol. 30, No. 1, January 1951

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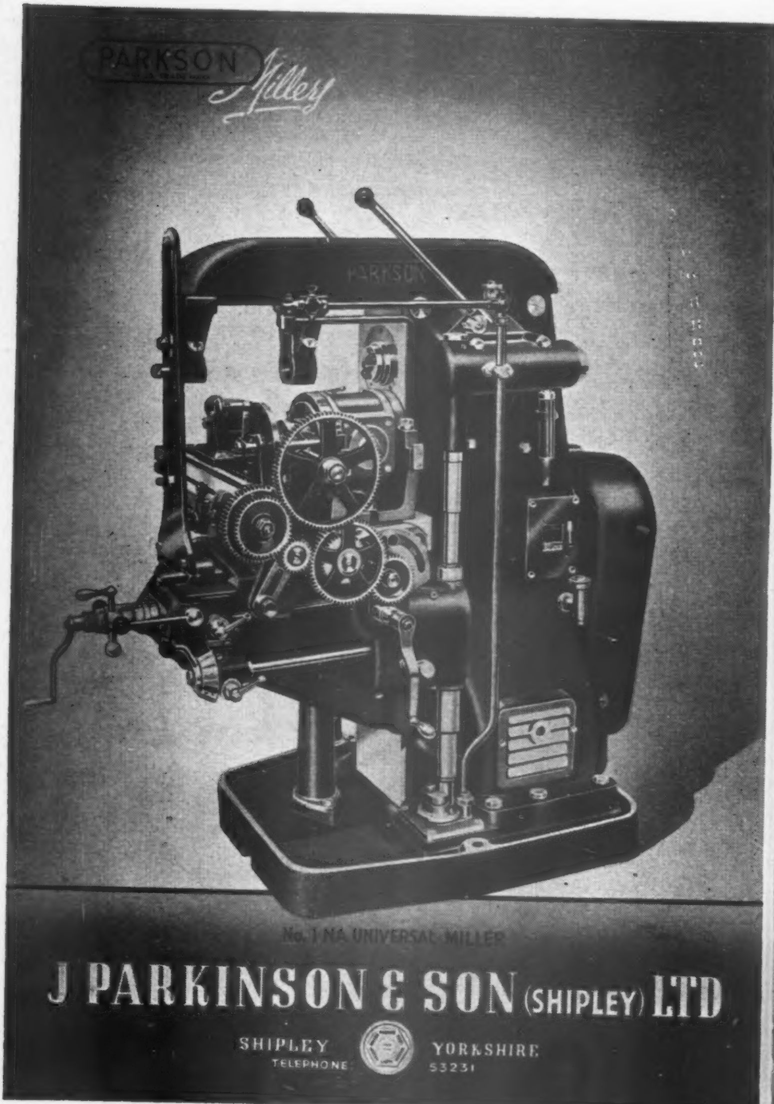
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THE JOURNAL OF

THE INSTITUTION OF PRODUCTION ENGINEERS

Vol. 30, No. 1, January 1951

Contents

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INSTITUTION NOTES

January, 1951

MEETING OF COUNCIL The next Meeting of Council will take place on Thursday, 25th January, 1951, at 11 a.m., at 36, Portman Square, London, W.1, followed by the Annual General Meeting at 4-30 p.m.

HARROGATE CONFERENCE Arrangements are now well in hand for the Conference which Council decided should be held from June 28th to July 1st next. The Conference Committee, under the chairmanship of the Chairman of Council, Mr. Walter Puckey, is supported by a number of strong Sub-Committees which are planning the details.

Mr. J. E. Hill, Immediate Past Chairman of Council, heads the Sub-Committee formed from Sections relatively near Harrogate, which is charged with the local arrangements and is concerned with reception. Dr. H. Schofield, C.B.E., Immediate Past President of the Institution heads the Sub-Committee dealing with the detailed arrangements of the programme.

The preliminary notice of the Conference was in the hands of members a month ago, and it is expected that an even greater demand for accommodation will arise than at Bournemouth two years ago. It is hoped that this time Sections will try to arrange Section parties in some hotels, so that the social side will not be overlooked.

Many members have already made their reservations, and it is hoped that other members who propose to attend the Conference will make their reservations as soon as possible in order to facilitate proper arrangements being made.

MEASUREMENT OF PRODUCTIVITY-CONFERENCE AT WOLVERHAMPTON The Wolverhampton Graduate Section have arranged a Conference on the Measurement of Productivity, to take place at Wolverhampton during January, 1951. Invitations to attend the Conference have been extended to the Birmingham and Coventry Graduate Sections, the Birmingham District Branch of the Institute of Cost and Works Accountants, and the Midland Region of the Institute of Economic Engineers.

The programme will be as follows :

Thursday, 4th January

A lecture on " A General Survey of the Subject " will be given by N. A. Dudley, Esq., B.Sc.Econ.(Hons.), M.I.Prod.E., at the Wolverhampton and Staffs Technical College, at 7-15 p.m.

Thursday, 11th January

A lecture on "The Reciprate Method of Time Study Analysis" will be given by D. J. Desmond, Esq., M.Sc., M.I.E.E., at the Wolverhampton and Staffs. Technical College, at 7-15 p.m.

Tuesday, 16th January

A Discussion Meeting will be held at the West Midland Gas Board Demonstration Room. The Discussion will be led by Professor T. U. Matthew, M.Sc., M.I.Prod.E. (Chairman), N. A. Dudley, Esq., Winston Rodgers, Esq., B.Sc., M.I.I.A., and D. J. Desmond, Esq.

NEWS OF MEMBERS

Mr. J. Bell, Associate Member, is now Production Manager of the Humberside Agricultural Products Co. Ltd., Brough, East Yorks.

Mr. J. Bergne-Coupland, Member, President of Lincoln Section, has been appointed to the Board of Directors of Ruston & Hornsby, Ltd., Lincoln.

Mr. F. H. Booth, Associate Member, has joined Broom & Wade, Ltd., High Wycombe, as Chief Planning Engineer.

Dr. S. Y. Chung, Associate Member, has received his Doctorate Degree in Mechanical Engineering from the University of Sheffield.

Mr. J. P. Ford, Associate Member, has recently been appointed to the Board of Brush Export Limited and Associate British Oil Engines (Marine) Ltd.

Mr. E. J. Hartley, Associate Member, has been appointed Lecturer in Automobile Engineering at Cambridgeshire Technical College.

Mr. P. E. Irving, Associate Member, is now Development Engineer to Chamberlain Industries, Ltd., Port Melbourne.

Mr. F. P. Laurens, O.B.E., Member, is now Director and General Manager, Engineering Works and Shipyard, at Vickers-Armstrongs, Ltd., Barrow.

Mr. A. Marsden, Associate Member, is now Toolroom Manager with Universal Metal Products, Ltd., Salford, Lancs.

Mr. J. H. Spurr, Associate Member, is now Manager of Vickers (Eastern) Ltd., Bombay.

Mr. L. Townend, Intermediate Associate Member, is now Methods Engineer at Rolls-Royce, Co. Ltd., Barnoldswich Division.

Mr. F. A. Gildon, Graduate, has been engaged on the staff of Ferranti, Ltd., as a Designer Draughtsman.

Mr. George Graham, Graduate, is now Planning Engineer at Plessey Co., Ltd., Ilford, Essex.

Mr. D. F. H. Rushton, Graduate, has been transferred from the Manchester Factory of Thomas Hedley & Co., to their manufacturing headquarters at Newcastle as Automatic Machinery Engineer.

Mr. N. Sherrington, Graduate, is now Estimating and Planning Engineer with the East Anglian Engineering Co., Lowestoft.

LONDON SECTION DINNER The London Section of the Institution of Production Engineers will hold their Dinner on Thursday, 1st February, 1951, at the Connaught Rooms, Great Queen Street, London, W.C.2. Lounge suits will be worn, and ladies will not be invited.

Tickets, price 25/- each, can be obtained from the Section Hon. Secretary, 50, Christchurch Avenue, Kenton, Harrow, Middlesex.

OBITUARY The Institution records with deep regret the death of Mr. H. J. Gibbons, Member, at the age of 73. Mr. Gibbons, who until his retirement in 1946, had been for over 20 years Managing Director of the Crossley Premier Engine Co., Sandiacre, was a Past President of the Nottingham Section of the Institution of Production Engineers, and during the last war served on the Institution's Executive, Finance and Research Committees.

He was also Past President of the East Midlands Branch of the Chartered Institute of Secretaries, a Companion of the Institution of Mechanical Engineers, Hon. Treasurer of the Nottingham District Engineering and Allied Employers' Federation, and served on the Engineering Advisory Committees of Nottingham University College and Nottingham and District Technical College.

RESEARCH PUBLICATIONS A number of copies of the following Research publications are still available to members, at the prices stated :

Report on Surface Finish, by Dr. G. Schlesinger	15/6
Machine Tool Research & Development	10/6
Practical Drilling Tests	21/-
Test Charts for Machine Tools, Parts 3 and 4	5/6 each.

These publications may be obtained from the Production Engineering Research Association, "Staveley Lodge", Melton Mowbray, Leics.

BOOKS RECEIVED "A Works Council in Action". Cadbury Brothers, Bournville. 1/-.

BRITISH STANDARDS The following Standards have recently been issued and are available from the British Standards Institution, 28, Victoria Street, Westminster, London, S.W.1, at the prices indicated :

B.S. 673 : 1950	Pneumatic Tools and Accessories (3/- post free)
B.S. 1658 : 1950	Housings for Hydraulic Seals (2/- post free)
B.S. 1678 : 1950	Cold Drawn Electrically Welded Mild Steel Boiler and Superheater Tubes (2/- post free)

These publications have been prepared under the supervision of the Mechanical Engineering Industry Standards Committee upon which the Institution of Production Engineers is represented by Mr. J. E. Baty, Member, Chairman of the Standards Committee.

THE LIBRARY The Library will be open between 10 a.m. and 5.30 p.m. on Mondays, Tuesdays, Thursdays and Fridays; between 10 a.m. and 8 p.m. on Wednesdays; and between 10 a.m. and 1 p.m. on the first Saturday of every month.

JOURNAL BINDERS Members are reminded that binding cases for the Journal are obtainable from Head Office, price 7/6 each post free. The cases, each of which will hold 12 issues of the Journal, are made of stiff board covered with imitation leather cloth, with gilt lettering on the spine.

CHANGE OF ADDRESS It would be of great assistance to Head Office if members would ensure that the business addresses contained in their records were up-to-date, and would notify Head Office as soon as possible of any change of appointment.

SCHOFIELD SCHOLARSHIP PAPERS

The winners of the Schofield Awards for 1950 will present their papers to the Institution at the following meetings :

9th Jan. " Welding in the Construction of Large Structural Components ", by W. N. Aspinall, Esq., Graduate, at The Geisha Cafe, Hertford Street, Coventry, at 7-15 p.m.

28th Feb. B. E. Stokes, Esq., Graduate, will give his paper in the Assembly Hall at the Chamber of Commerce, New Street, Birmingham, at 7-00 p.m.

ISSUE OF JOURNAL Owing to the fact that output has to be adjusted to meet requirements, and in order to avoid carrying heavy stocks, it has been decided that the Journal will only be issued to new Members from the date they join the Institution.

IMPORTANT In order that the Journal may be despatched on time, it is essential that copy should reach the Head Office of the Institution not later than 40 days prior to the date of issue, which is the first of each month.

SECTION MEETINGS

The following meetings have been arranged to take place in February, 1951. Where full details are not given, these have not been received at the time fr going to press.

February

1st **Glasgow Section.** A lecture on "Human Relations in Industry" will be given by W. P. Kirkwood, Esq., M.I.Prod.E., at the Institution of Engineers and Shipbuilders, 39, Elmbank Crescent, Glasgow, at 8-00 p.m.

1st **London Section.** There will be a Section Dinner held at the Connaught Rooms, Great Queen Street, London, W.C.2, at 7-15 p.m. for 7-45 p.m.

6th **Reading Sub-Section.** A lecture on "Foundry Practice" will be given by G. B. Partridge, Esq., A.I.M., at the Great Western Hotel, Reading, at 7-15 p.m.

7th **London Graduate Section.** A lecture on "Cost Control in Engineering Production" will be given by L. W. Robson, Esq., F.C.A., A.I.Prod.E., F.C.W.A., at the Institution of Production Engineers, 36, Portman Square, London, W.1, at 7-15 p.m.

7th **Liverpool Graduate Section.** A lecture on "Analysis of the phrase 'Near enough' (Permissible Tolerance) as Applied to Measuring Processes" will be given by E. Walshaw, Esq., A.M.I.Prod.E., G.I.Mech.E., at the Exchange Hotel, Tithebarn Street, Liverpool, at 7-45 p.m.

7th **Nottingham Section.** A lecture on "Artistic Metal Box Manufacture" will be given by G. Gledhill, Esq., at the Victoria Station Hotel, Milton Street, Nottingham, at 7-00 p.m.

7th **South Essex Sub-Section.** A lecture on "Material Handling" will be given by W. J. T. Dimmock, Esq., A.M.I.Prod.E., at the Mid-Essex Technical College, Chelmsford, at 7-30 p.m.

7th **Wolverhampton Section.** A lecture on "Mechanical Handling Techniques" will be given by J. Bain, Esq., at the County Technical College, Wednesbury, at 7-00 p.m.

8th **Southern Section.** A lecture on "Industrial Applications of the Lost Wax Process" will be given by A. Short, Esq., A.M.I.Prod.E., M.I.B.F., at the Polygon Hotel, Southampton, at 7-00 p.m.

9th **West Wales Sub-Section.** A lecture on "Materials Handling—Some Impressions of my Visit to America" will be given by W. J. T. Dimmock, Esq., A.M.I.Prod.E., at the Central Library, Alexandra Road, Swansea, at 7-30 p.m.

10th **Birmingham Section.** A Buffet Dance is to be held at the Botanical Gardens, Edgbaston.

10th **Yorkshire Graduate Section.** There will be a film and discussion on "Use of Rope" at the Great Northern Station Hotel, Leeds, 1, at 2-30 p.m.

February —*cont.*

12th **Sheffield Section.** A lecture on "Activities of the Production Engineering Research Association" will be given by Dr. D. F. Galloway, B.Sc. (Hons), M.I.Mech.E., A.M.I.E.E., M.I.Prod.E., at the Royal Victoria Station Hotel, Sheffield, at 6-30 p.m.

12th **Derby Sub-Section.** A lecture on "Generation of Fine Finishes by Machining Techniques" will be given by P. Spear, Esq., B.Eng., Grad.I.Prod.E., at the School of Art, Green Lane, Derby, at 7-00 p.m.

12th **Halifax Section.** A lecture on "The Economics of Foundry Mechanisation" will be given by J. Blakiston, Esq., A.M.I.Mech.E., M.I.Prod.E., M.I.B.F., at Whiteley's Cafe, Westgate, Huddersfield, at 7-15 p.m.

12th **Luton Graduate Section.** A sound film of the work of the National Physical Laboratory (Metrology Division)—"Precision Measurement for Engineers" will be shown at the Luton Library Lecture Hall, Williamson Street, Luton, Beds., at 7-30 p.m.

13th **Wolverhampton Graduate Section.** A lecture on "Electricity in the Factory" will be given by J. S. Brotherton, Esq., at Wisemore School, Walsall, at 7-30 p.m.

13th **Yorkshire Section.** A lecture on "Industrial Radiography" will be given by Dr. L. Mullins, M.Sc., F.Inst.P., at the Hotel Metropole, King Street, Leeds, 1, at 7-00 p.m.

13th **Birmingham Graduate Section.** A lecture on "Application of Carbides" will be given by a member of A. C. Wickman, Ltd., at the James Watt Memorial Institute, Great Charles Street, Birmingham, 3, at 7-00 p.m.

13th **Dundee Section.** A lecture on "Payment by Results" will be given by A. J. Charnock, Esq., M.I.Prod.E., at the Mathers Hotel, Whitehall Crescent, Dundee, at 7-30 p.m.

14th **Western Section.** A lecture on "The History and Development of the Automatic Loom" will be given by H. de G. Gaudin, Esq., B.A., M.I.Mech.E., at the Grand Hotel, Broad Street, Bristol, at 7-15 p.m.

14th **Liverpool Section.** A lecture on "Measurement of Productivity" will be given by Walter C. Puckey, Esq., M.I.Prod.E., F.I.I.A., at Radiant House, Bold Street, Liverpool, at 7-15 p.m. This will be a joint meeting with the Institution of Works Managers and the Institute of Cost & Works Accountants.

14th **Preston Section.** A lecture on "Ball and Roller Bearings" will be given by S. Critchley, Esq., A.M.I.Prod.E., in the Canteen, Clayton, Goodfellow & Co., Ltd., Atlas Iron Works, Park Road, Blackburn, at 7-15 p.m.

15th **Glasgow Section.** A lecture on "Education for Management" will be given by Lt. Col. L. Urwick, O.B.E., M.C., M.A., C.I.Mech.E., M.I.Prod.E., F.I.I.A., at the Institution of Engineers and Shipbuilders, 39, Elmbank Crescent, Glasgow, at 7-30 p.m.

15th **London Section.** A lecture on "Building a Liner" will be given by J. S. Redshaw, Esq., O.B.E., M.I.N.A., at the Assembly Hall, Royal Empire Society, Northumberland Avenue, London, W.C.2. (Craven Street Entrance, Charing Cross) at 7-00 p.m.

16th **Eastern Counties Section.** There will be a joint meeting with the Institute of Cost & Works Accountants, when a lecture on "Measurement of Productivity" will be given by R. G. Hooker, Esq., at the Ipswich Public Library (Old Foundry Road entrance), at 7-30 p.m.

February—*cont.*

19th **North Eastern Section.** A lecture on "Practical Application of Tungsten Carbide" will be given by H. Eckersley, Esq., at the Neville Hall Mining Institution, Westgate Road, Newcastle-upon-Tyne, 1, at 7-00 p.m.

19th **Manchester Section.** A lecture on "Mechanical Handling with Special Reference to the Textile Industry" will be given by F. T. Dean, Esq., M.I.Mech.E., M.I.Prod.E., at the College of Technology, Sackville Street, Manchester, at 7-15 p.m.

20th **Coventry Section.** A lecture on "Measurement of Productivity" will be given by Walter C. Puckey, Esq., M.I.Prod.E., F.I.I.A., in the Greyfriars Rooms, The Geisha Cafe, Hertford Street, Coventry, at 7-15 p.m.

20th **London Graduate Section.** There will be a visit to Hilger and Watts, Ltd., 48, Addington Square, London, S.E.5, at 2-30 p.m.

21st **Birmingham Section.** A lecture on "Steel Company of Wales, Ltd.—Progress and Development of Port Talbot" will be given at the James Watt Memorial Institute, Great Charles Street, Birmingham, 3, at 7-00 p.m.

21st **Edinburgh Section.** There will be a joint meeting with the East of Scotland Branch of Institute of Personnel Management when a lecture on "The Legal Side of Industry" will be given by H. Harman, Esq., B.Sc., at the North British Station Hotel, Edinburgh, at 7-30 p.m.

21st **Northern Ireland Section.** A lecture on "Marking Devices for Engineers" will be given by A. Throp, Esq., M.I.Mech.E., F.I.I.A., in the Municipal College of Technology, Belfast, at 7-30 p.m.

22nd **Leicester Section.** A lecture on "The Lost Wax Process" will be given by A. Short, Esq., A.M.I.Prod.E., M.I.B.F., in Room 104, Leicester College of Art and Technology, The Newarke, Leicester, at 7-00 p.m.

24th **Yorkshire Graduate Section.** There will be a visit to British Ropes, Ltd., Wakefield, in the afternoon.

24th **North Eastern Section.** There will be a visit to Pyrotenax Ltd., Hedgeley Road, Hebburn, Co. Durham, at 10-00 a.m.

25th **South Wales and Monmouthshire Section.** A lecture on "Fundamentals of Production Management" will be given by M. Seaman, Esq., M.Sc., M.I.Mech.E., A.M.I.E.E., M.I.Prod.E., at the South Wales Institute of Engineers, Park Place, Cardiff, at 6-45 p.m.

27th **Birmingham Graduate Section.** There will be a visit to A. C. Wickman Ltd., Wimet Division, Coventry, in the afternoon.

27th **Luton Section.** A lecture on "The Control of Quality in Large and Medium Quantity Production" will be given by J. Loxham, Esq., M.I.Mech.E., M.I.Prod.E., F.R.S.A., at the Small Assembly Room, Town Hall, Luton, at 7-15 p.m.

28th **Coventry Graduate Section.** A lecture on "Industrial Tool Rooms" will be given by C. Kingham, Esq., D.C.M., A.M.I.Prod.E., at Room A5, Coventry Technical College, The Butts, Coventry, at 7-15 p.m.

28th **Lincoln Section.** There will be an evening visit to Clayton Dewandre & Co., Ltd., Titanic Works, Lincoln, at 6-00 p.m. Members to notify H. Wright, Esq., Ruston & Hornsby Ltd., Boultham Works, Lincoln, before Wednesday, 21st February.

28th **Western Section.** A lecture on "Productivity" will be given by E. C. Gordon England, Esq., M.I.Prod.E., F.R.Ae.S., F.I.I.A., at Westinghouse Brake and Signal Co., Ltd., Chippenham, at 7-30 p.m.

VISIT TO SOUTH WALES BY THE MINISTER OF SUPPLY

On 27th September, 1950, the Minister of Supply, the Right Hon. G. R. Strauss, P.C., M.P., was the guest of the South Wales and Monmouthshire Section at an informal dinner held at the Park Hotel, Cardiff. The Section President, Mr. A. R. Northover, M.I.Prod.E., was in the chair.

The Loyal Toast having been honoured Mr. Strauss, proposing the toast of "The Institution of Production Engineers" said:

"This is the first time I have had the honour and the pleasure of being the guest of your Institution. Although I have met many of you before, this is also the first time I have seen so many Production Engineers all at once. I must say the sight of so many experts all in such apparent agreement with each other is most remarkable.

"I want first to pay a tribute to your valuable Institution. It is only 29 years since it was born, or conceived—I suppose that came first—that is, when its first 244 members met together to consider the post-war production problems of 1921. In less than a normal generation, the vigorous baby has grown to its great stature of to-day, with nearly 8,500 members throughout the Commonwealth, a professional body of high status and great value.

"It is not merely in your members that your strength lies, it is in your vigour, your knowledge and experience, and above all in your eagerness to pool ideas and seek ever better ways of doing things. And you are doing it very well indeed as I will show.

The Engineering Industry

"As Minister of Supply I am responsible for the engineering industry. Of course, I am a very fortunate Minister; this industry is doing very well, excellently, in fact better than any other group of industries.

"Let me quote a few figures:

(*i*) The gross output of the engineering industry, including vehicles, now exceeds £2,000 million per annum.

(*ii*) The net output of the industry, that is the value added by your work to the raw materials, is £1,250 million per annum.

(*iii*) The productivity of the industry, taking 1948 as 100, was 106 in 1949 and in the first half of 1950 rose to 114.

(*iv*) The exports of the industry are 42.5% of the manufactured goods exported.

"I hope these figures have not given you indigestion ; they should give you pride. Although productivity may have lost some of the magic it once had, it is still the measure of success. The productivity of the industry rose by 6% in 1949 over 1948, and this year it has gone up by 7% over 1949.

"This compares with an average increase over the rest of the industry of some 4½%, an achievement of which the engineering industry should be proud, and something for which we are very grateful to the Production Engineers.

"I have spoken of the growth and importance of your Institution and I want to touch on the status of your profession in this country. I am struck by the comments of many of the Anglo-American Productivity Teams on the high status of Production Engineers in America, and of the very large number of such technicians in managements in the States. I have no doubt that this is one of the reasons for the higher productivity of American industry. I look forward to seeing more of your profession in British industry and commend you to encourage engineers to join your ranks, at the same time taking care to keep your standards high.

Technical Education

"There have been grave gaps in our technical education in the past. The Government is already doing a great deal to fill those gaps and it is determined to do more. The figures I gave you a few moments ago show that we are an engineering nation, a vast workshop and to keep such a massive industry as yours efficient it is essential to maintain a constant flow of the technically educated men to the profession. Your own Education Committee has given valuable assistance to national committees on technical education, and your Institution is doing excellent work in training the next generation of Production Engineers. I ask each one of you to encourage the students and young men under your mature influence to equip themselves well, to respect your profession and to realise its value.

Research

"There is little need for me to stress to such a gathering as this the vital importance of research in every field affecting production. The Government is doing more than ever before to encourage research in industry. It does this by taxation allowances and also by a very large number of direct grants to research bodies.

"One of these is the Production Engineering Research Association, a most valuable organisation of which your Institution was the parent. I hope you are proud of your child and still give it some support.

"P.E.R.A. has now been an independent research association for nearly four years, financed jointly by industry and the Government

through the Department of Scientific and Industrial Research. Last year the Government assistance exceeded £30,000 and it is likely to be more this year. This is the measure of the Government's interest in your work and I hope the profession will make full use of the Research Association and its discoveries.

" Your own Research Committee is also doing encouraging work and I look with confidence to the results of the research you are doing with Birmingham University. I am sure that there is much to be learned about time study rating ; valuable knowledge to be applied to Industry.

" Your Committee's study of materials handling in British factories is very useful and together with the Anglo-American Productivity Team report on this subject, will show how to improve productivity by better Materials Handling methods.

" Wales during and since the war has built up many new factories and new industries. The production engineer has played a great part in making these projects successful. It is a little invidious to single out any one from the many cases of successful production. I am particularly impressed by one factory which I hope to visit tomorrow morning, with which your Chairman is connected. It began production in 1948 ; within six months the estimated output had been reached. At the end of the first year it had been doubled, in the second year there was a further 30% increase and this year production has increased a further two-thirds. The factory is now producing at four times its estimated capacity, with no building extension but entirely by planned organisation, utilising production techniques in which you here are so expert. This is a magnificent achievement and a striking tribute to your profession.

The Defence Programme

" We are all now concerned with rearmament. You will not expect me to give a list of contracts or production figures and to-night I am only going to touch on the effect the programme will have on production engineers. Many of you will not find much difference in your immediate activities. The work of the factories must go on, in many the proportion of service work may be very small, but full production must be maintained. Somehow, and this is when the call is especially directed to you, the production for defence must come out of increased productivity.

" Exports must be maintained and if possible expanded. The demands of the Services now being worked out must be met in full. None of us wants to cut his standard of living. I believe that you experts know better than anybody that by good planning, expert efficiency and good human relations the extra can be got sufficient to maintain our way of life and defend our homes against shortage and scarcity, as well as against threats of physical aggression.

" The present and the future are in our hands, it is for you to engineer the production. This is the job for which you are trained. The country looks to you with confidence, the Government will back you with all its power. It will scour the world for raw materials, it will strive its utmost for industrial peace.

" The production engineer is the key-man, his achievements have been great, he has earned the gratitude of the country."

The response was made by the President of the Institution, Major-General K. C. Appleyard, C.B.E., followed by the Chairman of Council, Mr. Walter C. Puckey. The toast of " Our Guests " was proposed by Mr. Northover, to which the Lord Mayor of Cardiff, Alderman George Williams, C.B.E., J.P., and Mr. W. S. Gray, Regional Controller, Ministry of Supply, responded.

Photo-Elastic Stress Analysis in Relation to Production Engineering

By S. WIDDAS*

Presented to the Eastern Counties Section of the Institution, 20th October, 1950

THE difficulty in presenting a paper on this subject is that it is unfamiliar to the majority of those hearing it, and in consequence it is necessary to give what is hoped will be sufficiently detailed information as to the method used, the optical principles involved, and the interpretation of the results, in addition to the function of the method in its relation to production engineering.

In designing any engineering structure there are many formulæ available for computing stresses in the various members of the structure, and the evaluation of the results is a purely mathematical process. In complex structures the mathematics become extremely involved and there is often a feeling of uncertainty even when results have been achieved.

But even the best known and reliable methods cannot compute with any certainty the stress concentrations which can, and usually do, occur at changes of section, and equally, for example, whether a stay bar in a structure will have to withstand its computed stress, or be over-stressed, or even be redundant when the structure is stressed in service.

Under such circumstances, some method by which stresses could be made visible would be of great assistance to the designer, and such a method exists in photo-elastic stress analysis.

THE BREWSTER EXPERIMENT This branch of physics really began as long ago as 1816, when Sir David Brewster carried out his now famous experiment. This consisted of loading a bar of glass centrally, with the ends supported, and examining the results with a polariser and analyser (which will be described in detail later on). He found that when no stress was applied to the bar, the whole of the field was dark, but when the glass beam was loaded the upper and lower parts transmitted light, whilst the centre remained dark. This effect disappeared when the load was removed, and he rightly concluded that it was due to variation in the optical properties of the glass when stressed.

*Chief Metallurgist, Ransomes, Sims & Jefferies, Ipswich.

Very little further work was done until about 1906, when Professor Coker started his classical researches on the same subject, except that he used celluloid in place of glass, owing to its greater optical sensitivity.

This marked the real beginning of photo-elastic stress analysis, and with the more sensitive celluloid available, a great deal of fundamental work was done, and the foundations firmly laid for the modern methods.

Naturally, improvements have been and are being made in apparatus, methods, and model materials, but the principles remain unaltered.

THE ORIGINAL DISCOVERY It is of interest to note that the original discovery and the pioneer research work were both British, but, as is so often the case, foreign workers have taken our ideas, and altered and improved them, and it is only now that this method of stress analysis is returning to its country of origin as an additional tool *in the hands* of designers.

One of the seemingly incomprehensible things about photo-elastic stress analysis is the use of a transparent plastic model to show the stress distribution in a metal article of similar shape, and it may be desirable to state the law governing this fact before proceeding to the actual instrument and its use.

The law is that within the elastic limit of the materials used, whether metal or plastic, the stress distribution under load is the same.

The only case where this law does not hold is where there are holes in the article. Here, for very accurate work, certain allowances have to be made, but the percentage error introduced is not very great, and unless very accurate results are required, the corrections need not be applied.

As photo-elastic stress analysis depends entirely on optical apparatus, the first thing to consider is the nature of light. Light may be defined as an electro-magnetic vibration, of similar nature to, but much shorter than, radio transmission. Where radio may have wavelengths of anything from several thousand metres down to the centimetre waves of radar, light waves are only a minute fraction of a millimetre. They are so small that a different unit of measurement has to be used in order to avoid very large numbers of noughts before the significant figure is reached.

The unit of measurement used for these small wavelengths is the Ångström unit, which is one ten millionth part of a millimetre.

The light to which the human eye is most sensitive is the green and yellow-green part of the spectrum, which is from about 5,000 to 6,000 Å, or roughly of the order of 1/50,000 of an inch as a mean value.

The spectrum itself, or, rather, the visible portion of it, ranges

from just under 4,000 Å to about 6,800 Å, and in this range occur all the colours of the spectrum, from blue at 4,000 Å to red at 6,500 Å and over.

Beyond the visible spectrum, at either end, are further vibrations, with infra red beyond the 7,500 Å, which in turn changes to the longer heat waves, and the violet and ultra violet below the blue-violet end of the spectrum, that is, from about 3,500 Å to 2,500 Å or less.

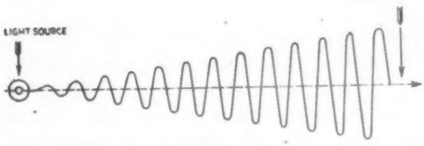

Fig. 1.

These light vibrations may be at any angle to the centre line of the ray, when looking along it, vertically, horizontally, or anywhere between.

Photo-elastic stress analysis depends on what is known as polarised light, which may be defined as light vibrating in one plane only.

As this paper is intended for engineers, possibly a mechanical analogy will be more easily followed, especially as the explanation is brief, than a much longer explanation of the theory of double refraction. (Figs. 1 and 2.)

Imagine a slit—horizontal if preferred—in a piece of very thin metal. The width of this slit is so small that light vibrating in a vertical direction cannot get through, but light vibrating horizontally can pass through the slit without interference, and light vibrating at any angle between these two positions will get through in part, depending on the horizontal component. So we finally get light vibrating in one plane only, that is plane polarised light. If the piece of metal is turned so that the slit makes an angle with the horizontal, the plane of polarisation will turn accordingly. This is the analogy of the polariser. (Figs. 3 and 4.)

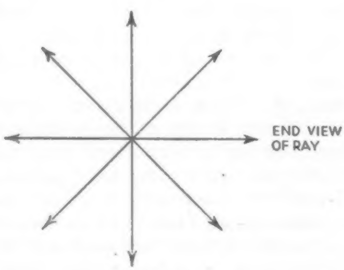

Fig. 2.

If we now take a second piece of metal with a similar slit, and place it on the same light axis, on the side of the polariser away from the light, we will notice some rather interesting phenomena. If the two slits are parallel, the polarised light from the first will pass

through the second without any interference, but if they are at right angles, the light passed by the first will be stopped by the second. This second piece of metal is known as the analyser. (Figs. 5 and 6.)

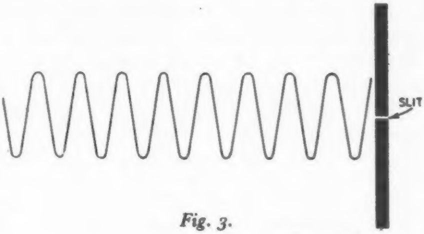

Fig. 3.

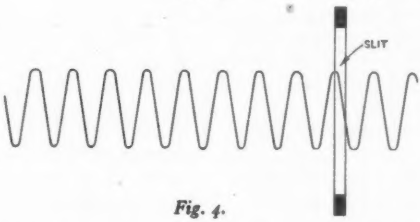

Fig. 4.

In actual practice, of course, such a method of producing polarisation is impossible, and so use is made of the doubly refracting properties of certain crystals. The three most important are Calcite, Iceland Spar and Herapathite. The first two are natural and the third is a complex synthetic organic compound.

Time does not admit of a detailed description of the first two, beyond stating that until comparatively recently, they were the only crystals available for producing polarised light, and owing to the small size of these crystals, a polarising prism made from them was unusually large if it gave a field of $2\frac{1}{2}$ in. dia.

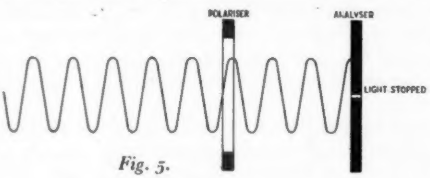

Fig. 5.

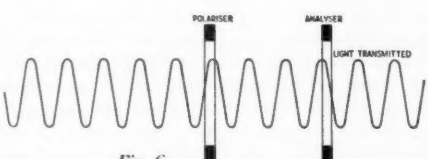

Fig. 6.

The third type of crystal, Herapathite, occurs as very minute needles, each of which can polarise light, but as single crystals they are useless owing to their very small size.

Some few years ago a method was found of embedding these crystals in cellulose nitrate or acetate so that they are all oriented the same way, and the resultant product behaved exactly as a large crystal in its effect in polarising light.

This synthetic polariser is the well known Polaroid, and can be obtained in sheets up to 12″ × 12″.

In photo-elastic stress analysis Polaroid has now almost entirely replaced prisms of Iceland Spar or Calcite, although the polarisation is not quite so complete.

Having now got a working idea of polarisation and methods of producing it, the next consideration is the optical system used in the instrument, known as a polariscope. (Figs. 7 and 8.)

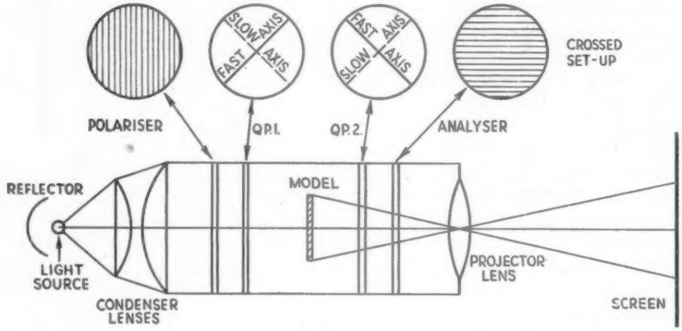

Fig. 7.

In general there are two main systems, with lenses and without.

The first system comprises a source of light, a lens system to give a parallel beam, polariser, model (in its stress frame), analyser, and projection lens. This system, up to a field of some 6″ to 7″ diameter, has big advantages in that the image of the stressed model can be projected on to a screen for instructional and demonstration purposes. The limitations are the cost of the lens system and the restricted field.

The lensless system can be used with a field of the maximum size of the polaroid available, thus enabling quite large models to be used. This method, however, suffers from the fact that projection is impossible, and large sheets of Polaroid are expensive.

In the models used in photo-elastic stress analysis, advantage is taken of the fact that certain transparent plastics, and glass may be included in this category, have the property that when unstressed they have no action on polarised light, but when stressed they develop the property of splitting the plane polarised light into two rays at right angles to one another and travelling through the model at different speeds. This property varies very greatly according to the plastic used. Some, such as glass and Perspex are very insensitive, requiring considerable stress to produce any result at all, whereas others, such as celluloid, cellulose acetate, phenol formaldehyde (Catalin 800), Columbia resin (CR. 39) and

the American bakelite BT. 61-893 are, in varying degrees, much more sensitive. The models and photographs for the purpose of this paper are all of CR. 39.

When a model, to be stressed in two dimensions, is placed between crossed polariser and analyser, it has no effect as long as it is not stressed, and the field remains dark.

On the application of a small stress, the model now appears light, except for certain dark shadows. On increasing the load, coloured bands are noticed, and the shadows become more intense and may alter their shape somewhat.

It is proposed to deal with this shadow pattern first, and the coloured later. The explanation of these shadows is that whereever the plane of polarised light coincides with the direction of a principal stress, the light passes through the model unchanged and consequently gets stopped by the analyser. At all other points, the two rays produced when the model is stressed, interfere with one another and the result is that a certain amount of light passes the analyser. These shadows are termed isoclinics. It follows, therefore, that an isoclinic line is the path, or direction, of a principal stress in relation to the plane of the polarised light. It also follows that if the polariser and analyser are rotated simultaneously, the isoclinics will change accordingly, so that by photographing or

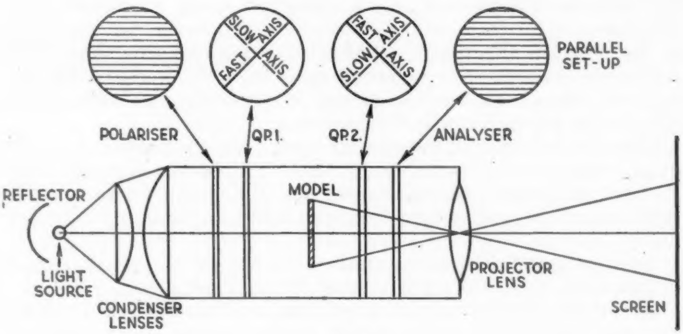

Fig. 8.

tracing these isoclinics at, say 5° intervals from—90° to +90°, a complete map is obtained of the directions of principal stresses in the model.

As it is often desirable to remove these isoclinics, it is, perhaps, better to describe how this is done before going on to the coloured stress pattern.

A description has been given of the production of plane polarised light, and now it is necessary to consider the production of circularly polarised light by means of quarter wave plates.

Certain substances, such as mica and "Cellophane," are capable of producing this effect. They have the property of splitting plane polarised light into two rays at right angles, the rays travelling through the plate at different speeds. When the plates have their optical axes parallel to polariser and analyser, the plane polarised light passes through unchanged, but when revolved so that either of the optical axes is at 45° to the plane of polarisation we get two rays of equal intensity but one is out of step with the other.

If the thickness of the mica is ·00126″ or the "Cellophane" about ·0005″, the difference in velocity of the two waves produced is one quarter of a wavelength, and as we have two simple harmonic motions at right angles to one another with a phase difference of a quarter of a wavelength the resultant is a circular motion, and the light, instead of being plane polarised is circularly polarised, the vibrations following a spiral path. It follows from this that circularly polarised light cannot produce isoclinics, and the stressed model only shows the coloured bands referred to earlier.

In practice, two quarter wave plates are used, one either side of the model and between the polariser and analyser. They are set with their optical axes crossed, i.e., the fast axis of one is at 90° to the fast axis of the second, and both are set at 45° to polariser and analyser.

The effect of crossing the quarter wave plates is that the second one takes the circularly polarised light from the first and exactly reverses the spiral motion, giving plane polarised light again, which now passes through the analyser.

The effect of putting the quarter wave plates in parallel, but still at 45° to the plane of polarisation is to turn the plane of polarisation through 90°, which, in turn means that the analyser will pass the light it receives, and the back-ground will now be light instead of dark.

This property of parallel quarter wave plates is used when it is desired to show the method of supporting the model.

Earlier in the paper it was stated that in addition to the isoclinic shadows there are coloured bands visible, and it is now time to consider their nature.

In permanently doubly refracting crystals, such as Calcite, ordinary light is split into two rays, at right angles to each other, which travel through the crystal at different velocities. In these crystals the amount of double refraction is fixed.

The materials used for models, however, do not show double refraction in the unstressed condition. Double refraction only appears when the model is stressed, and in proportion to the stress.

It disappears when the stress is removed. " At each point of a two dimensional stress system there are two planes at right angles to each other in which the shear stress is zero, and in which the normal stresses are a maximum or a minimum. These planes and stresses have been defined as the principal planes and principal stresses respectively, and the stresses are designated by P and Q ". (Frocht, Vol. I, p. 135.)

The two rays produced in a model when stressed are parallel to these two stresses, and as the difference between P and Q increases, one of these rays is retarded more and more in relation to the other. When these rays are recombined at the analyser, they interfere. Starting from a state where $P = Q$, there is no interference of the two rays, and the model remains dark. As soon as a difference appears between P and Q, interference starts and the result is that the shortest visible wavelength, violet, is extinguished and the complementary colour, yellow, appears on the screen. As the interference increases due to increasing load, the wavelength increases and the various colours, starting with violet, are extinguished in turn, leaving their complementary colours visible, so the colour band passes from yellow to deep red, deep blue, blue-green and bright green, and on increasing the load further, the sequence is repeated, giving rise to a pattern made up of bands of colour. Now as each colour is produced by a definite value of $P - Q$, these bands trace out the points where, for any colour, $P - Q$ is constant, and from this the bands are known as isochromatics.

Model materials are sufficiently sensitive to show retardations of anything up to 30 wavelengths, and in consequence the colour scheme is repeated over each wavelength, except that in the higher orders, there is mutual interference between the actual colours, resulting in a washing out of the tints, and the higher orders of isochromatics show only alternating bands of pink and green. Each repetition of any colour means that the retardation between the two points is equal to one wavelength of light, and if a difference of X in the value of $P - Q$ causes a retardation of one wavelength, any multiple of X will show itself as corresponding number of isochromatics, and the colour pattern can therefore be regarded as a series of contour lines defining the values of $P - Q$, just as in ordinary maps the contour lines define the values of heights.

One of the troubles in making exact measurements of retardations of one or any multiple of one isochromatic is the location of the change point from the green of, say, the first isochromatic to the yellow of the second. To obviate this, use is made of monochromatic light, where, instead of a wide band of light frequencies, only a very narrow band of the colour selected is used. The colours chiefly used for this purpose are the yellow from a sodium lamp, with a wavelength of 5,893 Å, the green from the Mercury

vapour lamp, with a wavelength of 5,461 Å, or the green Wratten screen No. 62, with maximum transmission at 5,350 Å.

The pattern now becomes one of black bands on a background of the colour of the light used, and as these bands are, especially in the higher orders, fairly sharply defined, the difficulty of determining the actual points of retardations of one or more wavelengths is largely overcome. (Fig. 9.)

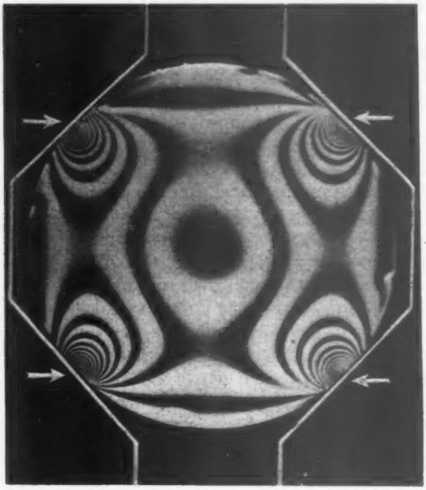

Fig. 9. Section of round bar compressed between V blocks (outlined in white). Arrows show points of load application.

The use of monochromatic light is chiefly in the photography of stress patterns, where, by the use of suitable plates or films which are sensitive to the colour of the light used, the resultant photograph is of black lines on a white background for the model, and either a black or white field as required.

In these monochrome patterns, the isochromatics are usually referred to as fringes, and this term is often applied as well to the coloured isochromatics.

When one examines a model which, for example, represents a section through a two diameter shaft subjected to a bending load in the plane of the model, either by white or monochromatic light, the pattern shows a number of parallel or nearly parallel fringes in the parallel parts of the shaft, but a greater number, with much closer spacing, at the radius joining the two diameters. (Figs. 10 and 11.)

As it has been already stated that the greater the difference between the P and Q stresses, the greater the number of fringes, the conclusion is reached that the stress at the fillet is higher than that in the parallel portion of the shaft. How much higher depends on the ratio of the fringes in the parallel part of the shaft to those in the radius connecting the two diameters. This, again, depends on the radius of the fillet and the type, whether circular or parabolic.

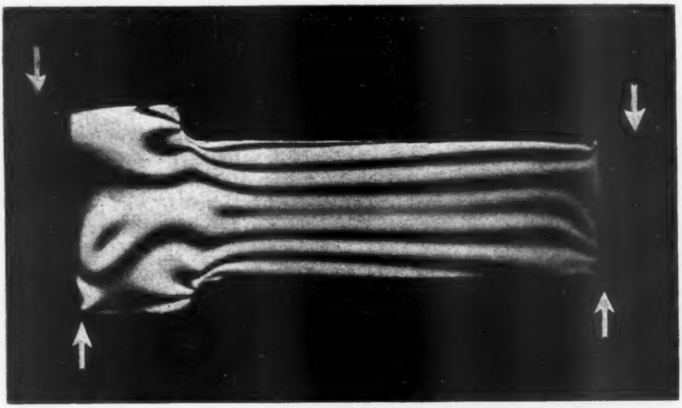

Fig. 10. Two diameter shaft with small radius. Pure bending.

In the matter of concentrated loads, such as a simple beam supported at the ends and loaded in the middle, there can be considerable discrepancies between the calculated stresses and those found in the photo-elastic stress analysis, and the examination of the fringe pattern will show that the actual stresses are higher than the calculated ones.

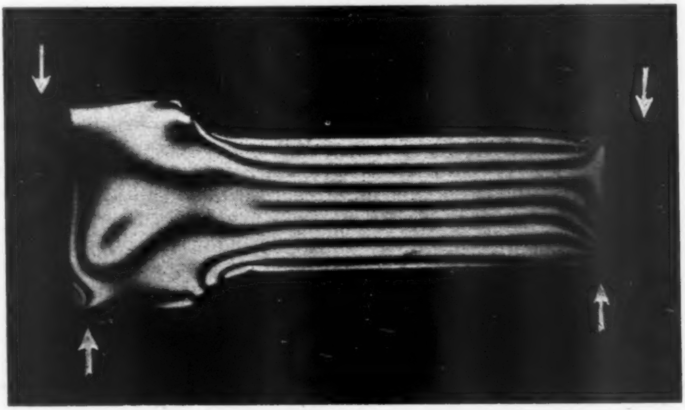

Fig. 11. Two diameter shaft with large radius. Pure bending.

It will occasionally be found, on examining a stressed model, that there are parts which appear to be completely outside the stress pattern, and may even show as nearly dark parts against the dark field.

This indicates at once that the part outside the stress pattern is carrying little or no load, and is therefore redundant. A typical case occurred some months ago. A steel fork, including a 90° bend, had been deliberately thickened up on the outside of the bend by the designer in order to stiffen it. Examination of the design on the polariscope showed that this "heel" was practically unstressed and was, in fact, unnecessary, so the part was redesigned without it. (Figs. 12 and 13.)

Hitherto, stresses have only been considered in two dimensions, and the question will probably be asked as to whether three dimensional stress analysis can be done. The answer, up to a point is yes, but although a great deal of work has been done in this direction, it is not yet considered to be sufficiently reliable. When heated, plastics of the type used in photo-elastic stress analysis soften, and if strained, will largely maintain their strained shape on cooling. The stress required to produce this strain remains when the model is cooled, it is, in fact, frozen into the model, and sections can be taken in any desired direction without appreciably upsetting the frozen stress pattern. It is, however, a particularly useful method of obtaining two dimensional stress patterns of certain articles. As an example, it may be desirable to obtain the stress distribution in an armature stamping. (Fig. 14.)

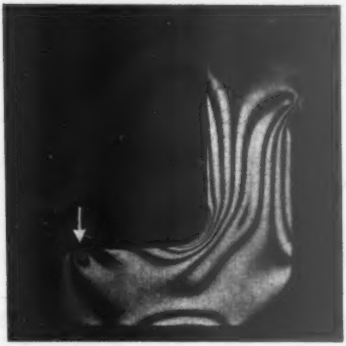

Fig. 12. Bend of "Forklift 20" fork, as originally designed. Note small radius and excess metal at heel of fork. Cantilever bend—arrow shows point of load application.

The method used is to mount the model of the armature stamping on a revolving table, heat the model and table to, according to the plastic used, 80-120° C., and start it spinning at high speed. During this period the centrifugal stresses strain the model, and the centrifugal stress is maintained until the model has cooled down to atmospheric temperature, i.e., it is kept spinning until it is cold. The model is then merely hung up in the polariscope, no loads being applied to it, and the resultant pattern examined for stress distribution.

It is not proposed to go into the mathematics of photo-elastic stress analysis, as to give the details of the formulæ used, and the method of using them would take up far too much time. In addition it should be stated that a considerable amount of useful data can be obtained by observation and simple arithmetic.

It is, for instance, obvious that if one finds four fringes at one part of a model and twelve at a change of section, the value of P — Q at the latter point is three times its value at the other.

For those who would like to go deeper into the mathematical side, the standard works will provide all the necessary information.

It has been stated that about 90% of all failures of engineering structures, whether buildings or parts of machines, are the result of faulty design, the other 10% covering abuse, wrong or defective materials, faulty inspection, and defective heat treatment.

Fig. 13. Bend of " Forklift 20 " fork, as redesigned with larger inside radius and constant thickness round bend. Cantilever bend—arrow shows point of load application.

The chief cause of failure, in the writer's experience, has been faulty stress distribution in design. Whilst it is comparatively easy to design a simple part to take definite and unvarying static stresses, using well tried mathematical formulæ, it is a very different case when the part designed has changes in section and is subject to irregular dynamic loads, and the majority of designers would in all probability have considerable difficulty in visualising the stress distribution, at, say, the change of section of a two diameter shaft.

The more complicated the shape and loading, the more complicated and time consuming will be the mathematics, and the greater

the need for checking the resulting design by some, preferably, non-mathematical method, and it is just these circumstances which make photo-elastic stress analysis a most useful method of checking design.

The best method would be for the designer, having finished the mathematical and drawing parts of his design, to consult with the photo-elastic section and have the design checked on the polariscope the models being suitable scale sections, stressed in the directions in which the actual part would be stressed in service. Visual observation would show at once whether there were any stress concentrations, their position, and the amount in proportion to the mean stress.

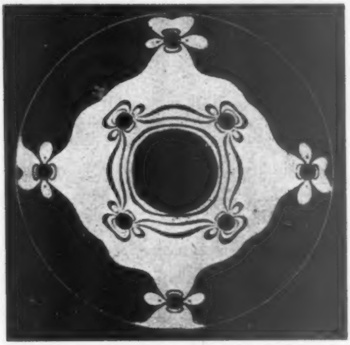

Fig. 14. Frozen stress pattern of disc with holes. Taken from Frocht, "Photo-elasticity", Vol. I, p. 338, with due acknowledgments.

If, for example, the designer had allowed a factor of safety of three, based on his calculations, and a stress concentration of four times the mean stress were found, it would be obvious that this part would fail very quickly at the point of stress concentration. Redesigning to reduce this stress concentration would follow, more models being made and tested until the weak spot was either reduced considerably in its stress concentration or removed entirely.

It might also be found that in certain parts of the structure, the stresses would be lower than the mean stress, indicating that there was an excess of metal at these parts, which should be removed, and only when the part has been modified to give as even a stress distribution as possible should the drawings be issued for production.

Broken parts are frequently sent to the laboratory for an explanation of failure. After the necessary material tests have been made, the parts are examined for the type of fracture, point or points of origin, and the drawings of the parts examined to see in what places stress concentrations were taking place. From the drawings, scale models are made, stressed, in the polariscope and examined for stress concentrations, and from observations of the stress patterns recommendations are made to the designer concerned with regard to modifications.

Usually, when parts fracture, the temptation is to add more metal to strengthen the part at the point of failure, whereas it is often preferable to reduce the amount of metal at a part where failure has not occurred to even out the stress distribution.

A very good example of this came to the writer's notice a few years ago. It concerned the fracture of a number of driving shafts, made from a high grade alloy steel. (Fig. 15.)

The shaft was a plain bar, splined at each end, and the fracture invariably occurred at the point where the differential gear fitted on to the end of the shaft. The fractures were all fatigue, caused by reversed shock torsion.

Examination of a part worn shaft showed that the splines on the gear, which was case-hardened, were digging into the splines on the shaft due to the twisting of the shaft under torsion in both directions. Instead of stiffening up the end of the shaft, it was decided to remove quite a lot of metal from the centre part, with the result that the final design was much lighter.

In the final design, the splines were cut short so that the gear overrode them, thus cutting out the digging in action of the gear splines, the next $\frac{3}{16}$ in. was machined to the root diameter of the splines, and the centre portion of the shaft was further reduced in diameter. This comparatively flimsy job was then put into service and the fracture troubles ceased.

Assuming that the material used is sound, it should here be stated that all fractures start at the surface, as the surface skin is always the most highly stressed part of any engineering component.

It follows from this that both in design and production special attention should always be given to surface finish, especially at changes of section, as quite small irregularities can cause considerable local increases in stress concentration, and in the case of highly stressed parts with a low factor of safety may make all the difference between satisfactory performance and fracture.

As an illustration of this, a broken petrol motor connecting rod of a type which has been very satisfactory was recently brought to the writer's notice.

The fracture was fatigue, and its position midway between the two bearings.

The first thing that was noticed was that on the edge of the connecting rod where the fracture commenced there were a number of rather deep transverse grooves, caused by a chipped trimming die when the stamping was trimmed. Examination of a model of this in the polariscope, stressed in pure bending with the grooved side in tension, showed considerable stress concentrations at the bottoms of the grooves, sufficient to reduce the factor of safety by half. Had this connecting rod been noticed by the inspection

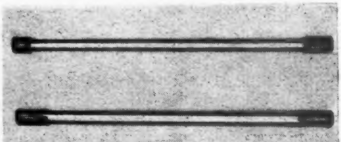

Fig. 15. N.U. electric truck driving shafts. Above: new design. Below: old design.

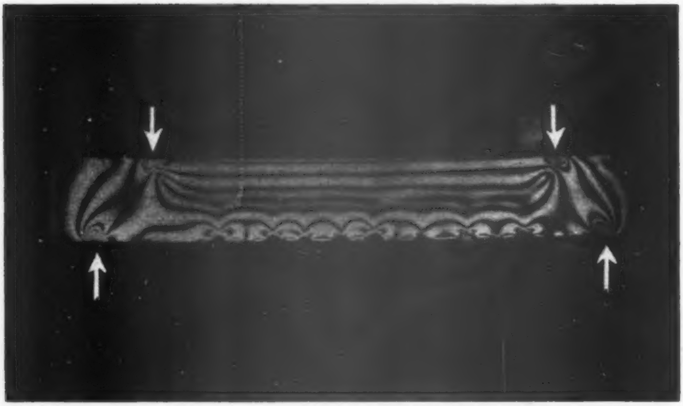

Fig. 16. Longitudinal section of connecting rod flange, showing grooves made by chipped trimming die. Pure bend. Grooved face of flange in tension. Arrows show points of load application.

department of the makers, and the grooves filed or ground out, it would not have failed. (Figs. 16 and 17.)

Quite small grooves made in machining a radius can have most disastrous effects on the strength of a double diameter shaft.

As production engineers are responsible for producing parts to drawing of the highest possible quality (as regards machining) in the shortest possible time and at the lowest possible cost, the question naturally arises as to how photo-elastic stress analysis is going to affect them.

It will affect them in two ways, firstly by the alterations in design, which may have a considerable influence on the number and sequence of machining operations, and secondly by the fact that greater attention would have to be given to finishing operations, especially to the blending of radii (which might be changed from circular to parabolic to reduce a stress concentration) with parallel parts of a component, and the very careful avoidance of machining grooves. Although it is admittedly a counsel of perfection, too much care and attention cannot be paid to surface finish, as it is always the surface which is the most highly stressed part of any component, and faulty surface finish can seriously weaken an otherwise excellent design.

This, in turn, involves more thorough inspection, not only for dimensions, but also for finish.

In connection with the effect of a re-design on production

methods, it might be desirable to revert to the case of the driving shaft referred to earlier.

The original lay-out comprised sawing to length, centring, machining to outside diameter, facing ends, splining and heat treatment. As redesigned, it involved, in addition, turning down to root diameter of splines, turning the centre portion to a smaller diameter, radiusing the change of section and grinding after heat treatment. A more costly job, admittedly, but one which has saved a lot of money in the breakages which have not had to be replaced, and has increased the customers' good will.

It does not always follow, though, that an improved design will be more costly to produce, as at the moment a component is being examined to eliminate breakages, and it appears that the altered design will be cheaper to produce as certain machining operations will not be required.

The number of causes of local over-stressing is so great that only a few have been mentioned. The principles stated above are also applicable to such nuisances, from the stress distribution point of view, of badly placed (and often worse machined) holes for lubrication, keyways, under-cuts in diameter to enable ball bearings to be pressed up against a shoulder, badly cut and torn screw threads. Probably those hearing this paper can think of quite a lot more of these stress raising details, but sufficient should have been enumerated to enable those responsible for design, production, and

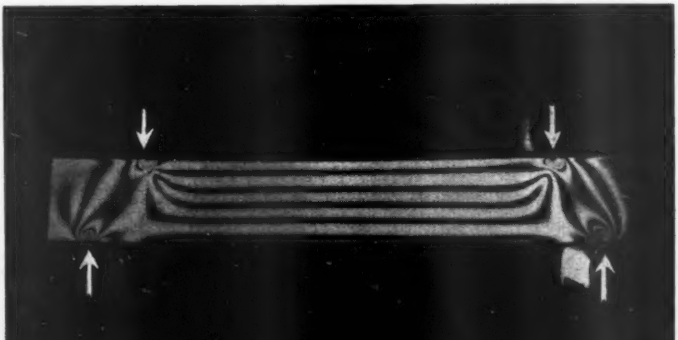

Fig. 17. Longitudinal section of connecting road flange, with smooth surface. Pure bending, lower side in tension. Arrows show points of load application.

inspection, to look on such stress raisers with a much more jaundiced eye than hitherto.

It is regretted that the time allotted for this paper has been so short that only a very sketchy outline of the principles and method of using the polariscope for photo-elastic stress analysis, and its effect on design and production, has been possible. If, however, this brief survey has aroused any interest in the subject—particularly among directors and designers of engineering firms—so that some of those present would like to go further, the paper, which is purely introductory, has served its purpose.

The old tag that a chain is no stronger than its weakest link is as true to-day as ever, and the purpose of photo-elastic stress analysis is to show the designer where these—often unsuspected—weak links are, and also to give him the necessary information as to how they can be strengthened, or, if far too strong, to be weakened until a design is reached where the stress distribution is reasonably even throughout.

It is always the little things which matter, the chipped die, the badly drilled oil hole, the rough thread which lead to the fracture of an otherwise adequately machined job, and the small radius, the sudden change of section, the undercut, and the misproportioning of parts which spoil otherwise good designs.

ACKNOWLEDGMENTS

The pleasantest, and to the writer the easiest part of this paper, is the making of due acknowledgments to those who have made this paper possible.

Firstly to Mr. H. H. Dawson, Works Director, for every possible encouragement and assistance, not only with this paper, but from the inception of the idea of having a photo-elastic section ; to Miss E. A. Gibbs, Works Photographer, for the preparation of the slides, and all other photographic work in connection with this paper, and to the Laboratory Staff, Mr. C. Hooley, B.Met., Mr. R. T. Buck, and Mr. R. J. Stinton, for the preparation of the models and the making of the required accessories for demonstrating them.

The Development and Modern Application of the Metallic Arc Welding Process

by G. CUBITT-SMITH, D.L.C., G.I.Mech.E., Grad.I.Prod.E., Stud.I.I.A.

This paper was awarded the London Section President's Prize, 1949-50

DURING the last century arcs were used as a method of obtaining high light intensity, and it was probably the realisation of the intense heat involved that lead to experiments to melt iron with it by Barnardos in 1885. This proved successful and opened up a new field for experiment in the early engineers' laboratories. It must be remembered that at this time very little was known about iron and its properties; consequently disappointments were frequent which accounts for its slow progress in the beginning.

With the arc established between the two poles, great difficulty was found in melting anything but the edges of plates. This could be overcome by two methods: (1) placing a magnet above the arc so that it repelled it; (2) replacing one of the carbon electrodes by the workpiece. It is the second that was a step nearer the present process. Having proceeded so far, the production of welds became mainly a metallurgical problem.

DEVELOPMENT OF THE METALLIC ARC WELDING PROCESS

However, as our knowledge increased in this field it soon became evident that welds made with this process were weak and brittle, carbon pick-up being the main cause. This meant that either the carbon electrode had to be replaced or a flux introduced to prevent it contaminating the weld metal. As is known, the electrode was replaced by the filler wire which proved more successful and is credited in history to Flavenoff in 1890. This was not the complete answer as it was still difficult to produce welds comparable with the parent material. The metallurgist discovered the welds were being contaminated with other elements, mainly oxygen, from the atmosphere. Kyellburg (1907) overcame this by lightly coating the electrodes in flux, which produced a protective atmosphere around the arc, and Strohmonger in 1911 introduced the present type of heavy coated electrodes. These briefly are the main early developments of the process from its inception, and from this point onwards engineers and metallurgists worked in close co-operation producing better equipment, parent materials and electrodes.

The next major development was the introduction of A.C. welding plant. This was desirable for two reasons—firstly, the adoption of 50 cycle A.C. supply as a standard for the country, and secondly, trouble had been experienced with the magnetic properties of the arc known as arc blow and it was believed that A.C. equipment would obviate this trouble. This was actually the case, but it brought with it another trouble, which was the maintenance of the arc as the voltage is zero 100 times a second, and this was sufficient to allow the tip of the electrode to cool and prevent the arc reforming. To overcome this a phase shift of 72° was introduced between the voltage and current cycles. This accounts for the low power factor namely (cosine 72°) 0·3 of arc welding plant. The restriking is further assisted by the protective atmosphere produced by coated electrodes, as it ionises the gap making the process quite smooth in operation.

A few words are now appropriate about the characteristics of welding plant. The ideal required is a constant current with varying voltage, which must be quite high for striking the arc, then a drop to a figure determined by the arc length, which in turn is dependent on the flux coating of the electrode, which varies between 20 and 45 volts. For the sake of the operator's safety, an upper limit has been placed on the open circuit voltage of both A.C. and D.C. welding sets which is 100 volts D.C. or R.M.S. Value A.C. This is stated in B.S.S. 638. However, in some places where even a shock of 100 volts may cause a man to slip and fall from a dangerous height, the open circuit voltage has been reduced to as low a figure as 60 volts.

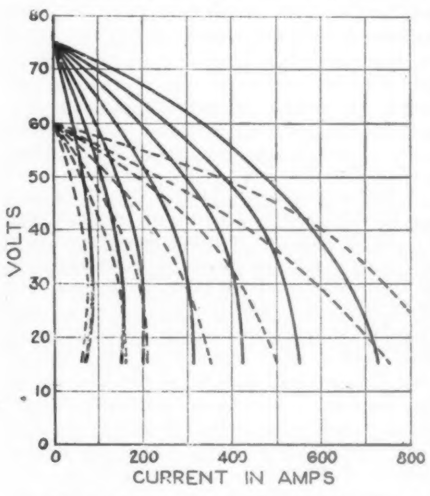

Fig. 1. Representative current/voltage characteristic for a 600 amp. D.C. single operator generator set.

In practice we must have a sloping characteristic so that the current may be controlled. As the voltage falls the current increases but the voltage being insufficient to support the arc the current returns to normal. A similar process

controls it in the other direction. A characteristic current/voltage curve for a 600 amp. D.C. welding generator shows this (Fig. 1). The process is also similar for an A.C. set.

Despite the endeavours by electrode manufacturers, they have been unable up to the present to produce an electrode suitable for welding some of the non-ferrous alloys using A.C. supplies. Recently engineers have produced a unit which generates a high frequency current (about 0.5 megacycles) of high voltage and negligible power which is superimposed on to the main current form. This obviates the restriking troubles and even starting difficulties on very light gauge wires (20 g.) so that with this equipment any of the metals welded previously only by D.C. are within the capacity of A.C. equipment.

Another development is electrodes with deep penetrating qualities which are obtained by using a high arc voltage. This is achieved by making the coating burn-off rate slower, thereby increasing the arc length and the depth of flux cone. Another new electrode is one which can be used in deep grooves because instead of producing sharp undercutting it produces a weld which is deposited equally up the sides as shown in Fig. 2. These electrodes use a flux containing a large percentage of iron oxide and some makes are able to satisfy the deep penetrating requirements although iron oxide cannot always be relied on to impart these properties. This point is important for two reasons. Firstly, those electrodes employing cellulose for the deep penetrating properties are adversely affected by overheating. That is, they lose their deep penetrating properties if the welder tries to use a higher than recommended current, his idea being to obtain greater power, hence penetration, which is reasonable enough. The iron oxide type operates in exactly

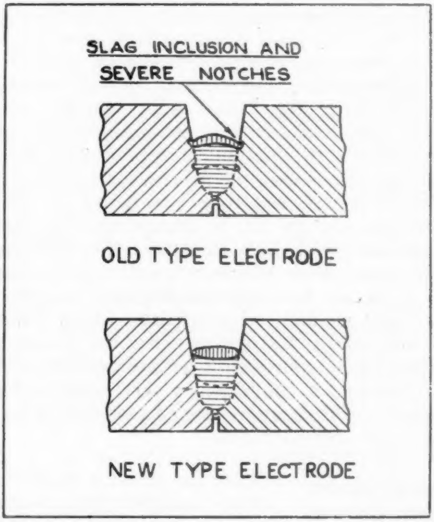

Fig. 2. Weld deposits in deep grooves.

the reverse way. Secondly, the cellulose type produces sharp undercut and notch effects which unless removed reduce the weld's notch resistance considerably. The iron oxide rod does not.

During the war there was a strong sway in favour of manipulating workpieces and using heavy gauge rods. These rods are still available to British industry up to $\frac{1}{2}''$ core diameters requiring currents of the order of 600 amps., but they have been used manually using up to 1,000 amps. with a mean arc voltage of 32 volts. However, since the war, the tendency has been to reduce the size slightly and some firms have gone right back ; this will be discussed in more detail later.

AUTOMATIC PROCESSES

These can be divided into those using continuous electrodes and others. By far the most important and successful are the continuous type which again are divided into two major processes : (*a*) Submerged arc or Union melt process ; (*b*) covered electrode type as developed by Fusarc and Metropolitan Vickers. The others suffer from a difficulty of reloading individual electrodes without breaking the arc. To overcome this the machines are necessarily more complicated, adding to the number of parts to go wrong in service.

One other form of arc welding used for mild steel which should be mentioned, is a process known as stud welding. This process requires a different current voltage curve, but the metallurgical features are the same as in metallic arc welding. The main difference between the processes advocated by different manufacturers is the method of applying the flux. The function of the equipment used in the process is to regulate the heat by controlling the amperage and time which are set for the varying operating conditions. An arc is drawn between the steel and the parent material after which the stud is plunged into the molten pool, the porcelain surround preventing the molten metal from splashing out.

A recent American development of this process is a method of arc spot welding on thin plates about $\frac{1}{4}''$ max. in which an arc is drawn in a similar gun between the parent material and a tungsten electrode surrounded by an atmosphere of inert gas. Although its application is limited it is very suitable for quickly spot welding assemblies that are too big or awkward to be handled in an ordinary spot welding machine.

METALLURGICAL CONSIDERATIONS

I assume that my readers are reasonably familiar with metallurgical characteristics of iron and steel so only brief reference will be made to some of the more important reactions that take place.

An ideal weld is one that has the same physical properties as the parent material, but this in practice is very difficult to obtain owing to the metallurgical changes in the structure of the parent

and weld materials in the heat-affected zone. So that undesirable products of the transformation may be avoided, careful consideration should be given to welding procedure and post-welding heat treatment for each particular material composition.

In welding heat is used to melt the parent materials locally and fuse them together, often with the addition of a filler material. There is one notable exception, the recently developed process of cold welding aluminium. The local heating produces a very severe gradient which causes changes in the heated zone ; these are, structural transformation, crystal size, and thermal expansion and contraction.

STRUCTURAL TRANSFORMATION Structural changes take place when iron or plain carbon steel is heated and cooled, but differing physical properties are characteristic of certain structural forms. The changes that take place in plain carbon steel heated or slowly cooled is represented in what is known as the Iron/iron carbide ([1]) equilibrium diagram and indicates those forms of iron in equilibrium under specified conditions. The austenite transformation is the most important from the welding engineers' point of view as this determines the physical properties at ordinary temperatures. This is decided by the rate of cooling as shown schematically in Fig. 3 which indicates the time required for nucleation and complete transformation : the products formed at different temperature ranges are also indicated. These "S" curves as they are known, vary for every different carbon ratio in the steel.

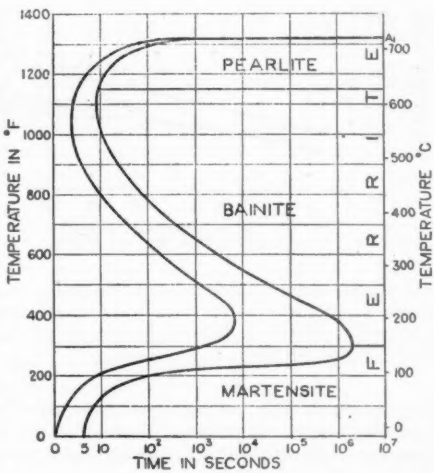

Fig. 3. Schematic "S" curve for a 0.3% carbon steel.

The trend is for the times required for the reaction and the hardness of the products formed to decrease, as the carbon content is reduced. The significance of this is important when it is remembered that the ductility usually increases as the hardness is decreased.

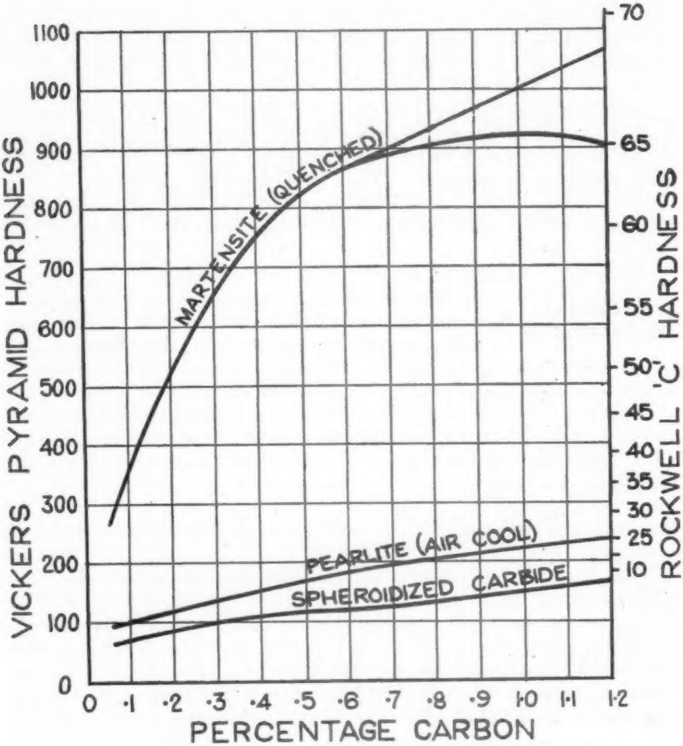

Fig. 4. The hardness of carbon steels in three structural conditions. Top: Fully hardened martensite. Middle: Lamellar structure (with proeutectoid constituents as formed in normal cooling after rolling). Bottom: Carbide coarsely spheroidised, minimum hardness commercially obtainable.

Fig. 4 shows the variation in hardness for different products of transformation at various carbon contents. These changes are influenced greatly by alloying elements present, and a brief survey of their effects is given later.

Note that Bainite is not shown. Little is known about this product as it is very difficult to obtain consistently; its properties lie somewhere between Martensite and Pearlite in the hardness and toughness scales.

Crystal Size. The crystal size depends on :

1. Size of Austenite crystals ;
2. Amount of cold work (2) ;
3. Size and amount of inclusions (3).

SIZE OF AUSTENITE CRYSTALS

As a form of iron is heated to a temperature approaching its lower transformation point crystal growth begins, the rate increasing until the temperature reaches this point when re-crystallisation refines the grain size ; the growth is repeated in the Austenite range. The large Austenite crystals retard nucleation and complete transformation during the following cooling cycle.

A steel that is cold worked has elongated crystals produced by twinns and slip along cleavage planes which occur during plastic deformation. These crystals consequently have large ragged boundaries which favour re-crystallisation at a temperature below the lower critical AcI. Hot peening makes use of this property to produce a fine grained weld, but requires very strict control otherwise cracking will occur if the weld tends to be blue brittle.

SIZE AND AMOUNT OF INCLUSIONS

Inclusions retard grain growth by obstructing atomic movement in solid solution but are undesirable as they often contain objectionable alloying elements. They also promote nucleation but increase transformation time.

The volumetric changes produced by heating followed by cooling can produce two types of stresses : (1) Shrinkage ; (2) Residual.

One of the physical properties of metals is to expand on being heated approximately linearly until they reach a transformation temperature where a sudden change in volume occurs. Alpha iron occupies a greater volume than gamma from which it transforms in cooling, but Martensite[4] has the lowest specific gravity—greatest volume. As the Martensite transformation takes place at a relatively low temperature, 150° C., the metal is fairly hard ; the reaction produces high compression stresses and the expansion may result in cracked crystals. This weakens the metal which may fail as the contraction stresses increase again, or under sudden overloads in service. After which normal contraction continues until room temperature is reached.

These crystal cracks will not be visible except under a microscope. This necessitates special precautions in welding steels liable to form Martensite in the heat-affected zone. The remedy is to preheat to 200° C., preventing the formation of Martensite until all welding is completed and the welded assembly can be cooled very slowly through the Martensite transformation range or, preferably, annealed without cooling to change the iron form. Annealing will not heal crystalline cracks once they have formed.

RESIDUAL STRESSES Linear contraction stresses the welds which may cause distortion in the welded components when proper precautions have not been taken ; otherwise the weld metal should flow plastically ; when the yield stress is reached it will not crack unless the metal has blue brittle tendencies.

Up to a short while ago engineers believed that residual stresses added to load, and this phenomenon has been used to account for some failures in the past. However, this theory could not be proved practically and we now know it is not true.

These stresses are not detrimental to the load carrying capacity of the weldment nor do they seriously impair the ductility of the material. But they will affect slight dimensional changes when the weldment is machined so that it may be more economical to stress relieve the component than machining, resetting and machining again two or three times reducing the depth of cut each time. As a general rule it is advisable to stress relieve all machined tool components and other components where slight movement of machined faces may be detrimental. For further information see the British Welding Research Association's report on Stress Relief.

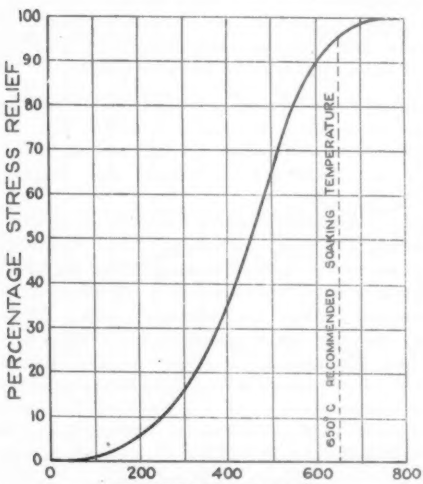

Fig. 5. Percentage relaxation of residual stress in mild steel structures.

Fig. 5 shows the relaxation of stresses in mild steel fabrications; this is commonly referred to as stress relieving[6]. This also tempers any hard zones in the weld area promoting re-crystallisation in cold worked metal. The degree of cold working produced in the weld zone by contraction stresses is not sufficient to induce re-crystallisation of the heat affected zone. The cementite is also spheroidised slightly, and from Fig. 4 it will be noticed that this is the softest form of steel commercially obtainable when fully treated. These points are now regarded as the important assets of stress relieving.

EFFECT OF ALLOYS

Alloys in steel[7] cannot be dealt with in a few words, but an endeavour will be made to remind readers of the general trends produced by various elements that are important from a welding standpoint.

Carbon C. This has been dealt with briefly in the preceding section, and is easily the most important alloying element in steel. It should be kept below 0·25% for welding.

Sulphur-S forms iron sulphide which solidifies at 925° C. promoting hot cracks by extension of the mushy state ; 0·05% S. can be regarded as a maximum.

Manganese-Mn. is a remedy for sulphur as it forms a harmless compound, Manganese sulphide (MnS) but must be present in quantities three times that of sulphur to eliminate completely its effects. Manganese is also slightly more prone to form carbides than iron but it is mostly present dissolved in ferrite at low temperatures. It is easily burnt in long puddling periods which should be avoided in the welding process. Mn in excess of 1·0% should not be melted without special precautions being taken to avoid deep hardening.

Phosphorous-P. produces banding which makes material weak in certain planes. Allowable maximum for welding, 0·06%P.

Silicon-Si. Powerful deoxidiser and dissolves in ferrite.

Copper-Cu. does not form carbides and will only dissolve in ferrite up to 0·8% max. This figure should not be exceeded for normal welding purposes.

Aluminium-Al. A powerful deoxidiser, hastens transformation of Austenite and increases fluidity.

Alloying Elements Dissolving in Ferrite.P. Si., Mn, Ni, Mo, V, W, Cr, Al and Cu up to 0·8% max. dissolve in ferrite, hardening it. Ferrite is stabilised by them with two exceptions ; these are Mn, and Ni, which stabilise the Austenite and in certain percentages prevent Austenite transforming at all. Two familiar steels of this type are 18% Cr, 8% Ni, 0·1% C and 11-14% Mn, 1·0-1·9% C. In the latter case a little Martensite may form but it is harmless. Below these percentages they produce deep hardening properties which are undesirable in welding.

Alloying Elements forming Carbides. Mn, Cr, Mo, V, Co, T, are prone to form carbide in increasing intensities respectively, which tend to reduce the carbon content in surround ferrite ; the carbide acts as inclusions. Alloys with high carbide forming tendencies such as T tend to force other elements to dissolve in ferrite.

Dissolved alloys generally delay nucleation by impeding reacting atoms and strengthening the iron forms. Cobalt is the only exception ; it hastens nucleation and transformation.

Alloying Elements which lower the Critical Cooling Rates. Ni, Mn, Cr, V, Mo, lower critical cooling rates in progressively increasing amounts.

HEAT DISTRIBUTION IN WELDING

We have seen how various conditions affect the products of transformation; the cooling rate often determines the physical properties of the welds, especially in plain carbon steels. Fig. 6 shows a schematic diagram of the heat distribution during welding and the changes in crystal size after welding in a rolled and annealed

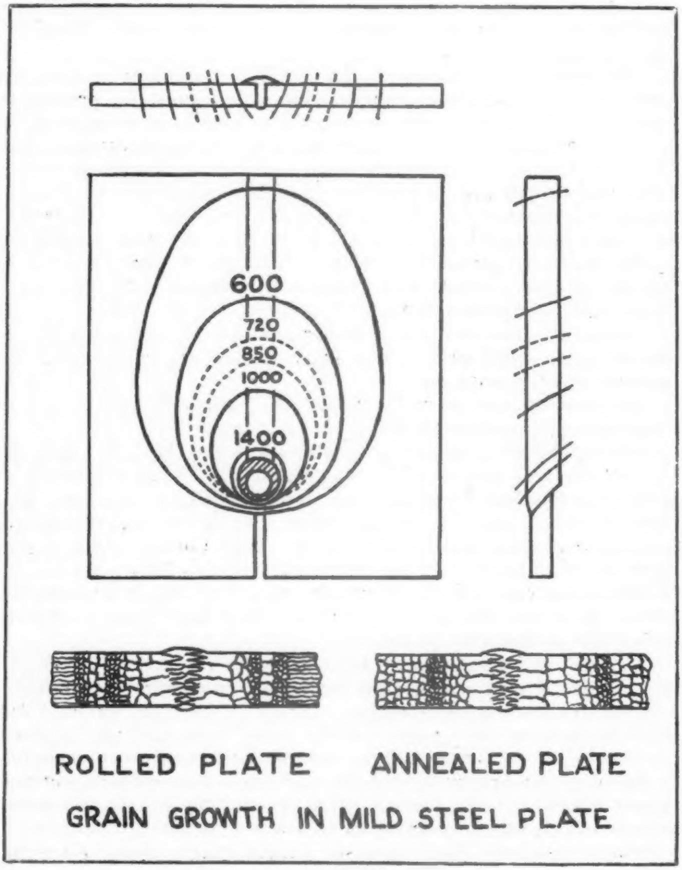

Fig. 6. Heat distribution and effects during welding.

M.S. plate. In rolled plate there are two crystallisation points as would be expected. In this country three types of welding are in general use ; these are :

1. Light current (multi-run). 300 amps. and below ;
2. Heavy current including automatic ;
3. Austenitic welds.

The tendency is for heavy current welding to increase where possible. This is a point of great controversy between engineers. From metallurgical considerations a compromise between the two will probably prove to be most satisfactory in the end, for the following reasons :

In multi-run welding, the first run is fully annealed by the second and so on as the number increases. It can be performed in any position but it suffers badly from cracking due to low heat input and chilling of the weld (probably forming objectionable Martensite). Low penetration prevents the removal of mill scale and rust by flotation into the slag ; instead it enriches the junction with these undesirable elements which may cause cracking. There is greater distortion due to accumulative effects of each run.

In heavy welding, there is less distortion, good penetration and removal of mill scale, cheapness when manipulation is not required, and less chilling of the weld. It suffers from lack of annealing when welds consist of single runs and is very limited in welding position, down hand only being really suitable.

Austenitic welding. This type is used on very rigid components ; where high weld ductility is necessary this is obtained in the 18% Cr, 8% Ni electrode which is Austenitic at all temperatures, but care must be taken to avoid excessive penetration as weld metal will be diluted by mild steel to a dangerous percentage (9% Cr, 4% Ni, an air hardening steel). This state of affairs will produce Martensite in the junction area, but the layer is so thin and distributed that it is of no consequence. These welds are extremely hard owing to carbide precipitation due to chromium's higher carbide-forming tendency, and should not be used where welds may later be machined.

SUMMARY Summarising this section it is essential to ascertain the metallurgical changes that may result in undesirable forms of steel in the weld zone. This is determined by number and quantities of alloying elements present and the cooling rate of the weld, dependent on the mass of surrounding material receiving heat by conduction. Heavy current welding including deep penetration should be used, and a second run should be made where welds are heavily stressed. Manipulate weldments where it is economic, otherwise specially prepare joints for down hand welding. Where positional welds have to be used (site work) the

parent metal should be cleaned of all scale and thick sections pre-heated from the opposite side.

Austenite welds should be used for rigid components as advised by welding engineers, whose instructions should be carefully adhered to as they are given for sound reasons.

The Americans have graded their steels into three categories, namely :

100 easily welded.

200 moderately easily welded.

300 difficult to weld.

Below is a specification for weldable MS castings :

Two grades each having 0·7% Mn maximum, 0·5% Si maximum. Grade " A " : 0·25% C maximum ; " B " : 0·35% C maximum. Alloying elements should be restricted to : 0·5% Cu maximum, 0·5% Ni maximum, 0·25% Cr maximum, 0·25% Mo plus W. Total of all these elements must not exceed 1%.

USES OF DIFFERENT JOINT DESIGNS

The metallic arc process is available in numerous forms as a production tool today. As it is not always possible to obtain the ideal conditions, it is more essential that we use the right form in any given set of circumstances to obtain a weld at the lowest cost. To achieve this in any factory we must have the closest co-operation between the production department and the design and drawing offices.

The particular joint design most used in a company should vary with the equipment it has at its disposal. We have seen that there are three types of welds that can be made which I have conveniently divided into multi-run (low current), heavy current and automatic. The difference between the first two is only the capacity of the equipment, the third is special. The difference in welding speed and therefore cost, shows that the importance of the equipment is significant.

Multi-run welds can be made in any position and are therefore most suitable for site work and weldments that for some reason may not be manipulated. These welds are expensive to make, as deposition rates are slow and there is extra fatigue to the welder especially in overhead position.

Heavy current welds can only be made in the down hand position. They have the advantage of high deposition rates and a sounder weld deposit.

The automatic processes have many advantages over their manual counterparts which are, consistency of deposit, good penetration properties, greatly increased deposition rates, lowering of fatigue but of course there are some disadvantages too ; no allowance can be made by the machine for poor fit up of joints ; they can only be used in the down hand or horizontal position

which may necessitate a large amount of manipulation and time to set up the welder. The last two points weigh heavily against these processes especially in the jobbing industries where every successive weldment varies in size. However, the Americans have developed and are using manually operated heads on automatic welders; these benefit from the higher deposition rates and to a certain extent most of the other advantages are retained without the disadvantage of heavy set up expenses, but correct manipulation will still be necessary.

Up to the present the Fusarc or manufacturers of the covered electrode processes have not developed a manual head. I feel these manufacturers could profitably consider this project.

If joints are designed with a view to welding the component without excessive manipulation and this can be done, I am certain a job of equal quality could be obtained with three or four turns. This would be a far cheaper proposition than loading on expensive manipulators, apart from the capital expense of a manipulator.

The component requires a crane to lift it on, some time to clamp it in position and the reverse to remove it. The welders must work at heights, climb ladders and often come down while the component is manipulated. Often a weldment will have to be turned over and reloaded, this may have to be repeated two or more times.

One example is a hydrogen-cooled alternator; here a similar state of affairs exists, at first they were welded by the multi-run method. Leaks appeared, their cause was often traced to a point some feet from the point where the leak had occurred. A cracked first run or incomplete penetration with second and third runs were responsible.

A heavy manipulator was constructed and this showed better results but the loading and operating costs for such a large component were exorbitant. The trouble and expense again could have been avoided by a different joint design.

Naturally, being concerned with the electrical industry, my examples are of electrical components but I am certain these points apply equally to many other fabricated components. Further more you will notice that often the change of joint design brings the weld nearer the neutral axis, which is one of the most effective methods of reducing distortion followed by weld sequence which is in no way hampered any more than it is on a manipulator; in many cases it is improved.

In Fig. 7 I have shown a comparison of some of the alternative preparations available for different types of joints. I would like to alleviate this apparent fear of the joint that appears to be more complicated to make. If the edge of the joint is machined the extra time required to rough a " J " is negligible; the same applies for flame cutting as it can still be cut in one pass using three cutters

on one main head. The advantages gained by far outweigh the extra gas used.

Stud welding, when it was first introduced in this country, was applied more or less indiscriminately and a lot of trouble was experienced. Firstly, on jobs in the factory, adequate provision

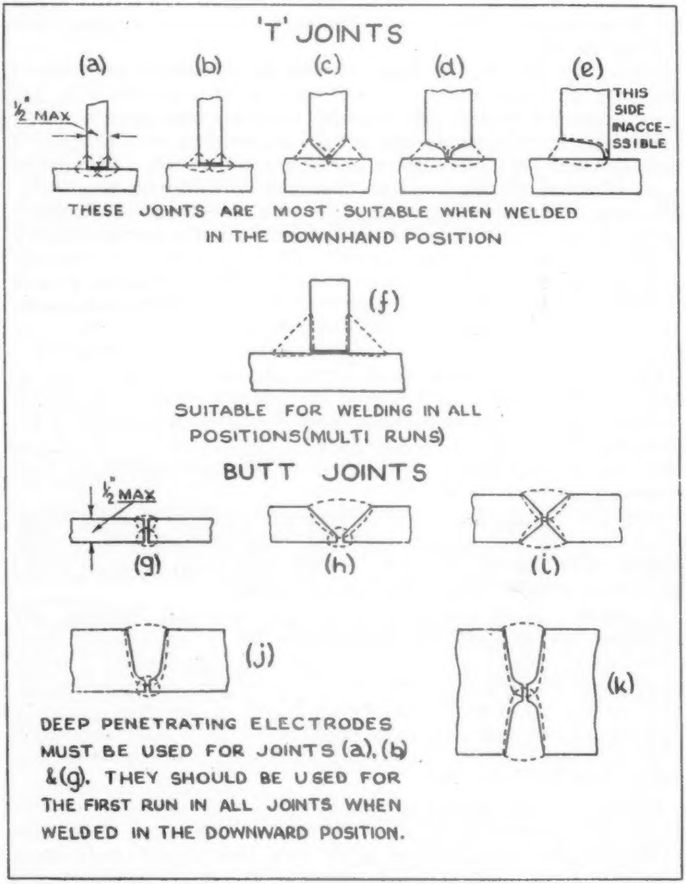

Fig. 7. Alternative joint preparations.
(Note : Weld metal and penetration shown by dotted lines).

must be made to ensure the studs do not get damaged after welding before arriving in the assembly bay. Secondly, as failures are difficult to repair on site, very strict supervision must be maintained to ensure proper working conditions as the process is semi-automatic. To obtain the full benefits of the process flanges should be reduced to save steel ; in many cases the wrapper is suitable as a flange with stud welding. Providing these precautions are taken stud welding can be used very satisfactorily on many fabrications, and will show great savings in operation times and material costs if full advantage is taken of the process.

MODERN APPLICATION

The relation between the joint design and welding process has already been discussed. But this is only one aspect of an immense problem, as there will be a large amount of other equipment required which will vary in type and size according to the type of components to be produced. It is not surprising, therefore, that some companies may be reluctant to adopt this method of manufacture when there are so many problems to be faced. If this is the case, I should like to draw your attention to some monetary aspects of the subject, and say that if the problems are treated with caution they can nearly always be satisfactorily solved, and of course, there are a vast majority of weldments which present no problem at all.

My first example is of a water turbine rotor hub—the approximate cost is £2,200. An equivalent casting would cost £4,180 which shows a substantial saving of nearly £2,000.

Now a comparison between a cast iron bedplate and a fabricated one. Here again we can show savings amounting to £58, the cost of the cast iron bedplate being £144 and fabricated £86. Note these figures are only comparative, as they will vary from firm to firm and with different methods of costing.

These savings can only be made if there is close co-operation between the design department and the production department. This is often difficult to obtain as a design department will have been used to castings and used to compound curves, etc., for good appearance. They will find it hard to alter their ideas for the ease of production by fabrication and often they just copy the equivalent casting by replacing sections with mild steel plates. This method is wrong and will hardly ever show savings for reasons I have described ; this especially applies to joint design.

CONCLUSIONS

The main points to be drawn from this paper are :

1. Always ensure that the material is suitable for welding. Examine its chemical composition and metallurgical condition.

2. Assuming the equipment is available, high deposition rates will produce the cheapest and soundest welds if the conditions are suitable.

3. Joints must be designed to suit the available equipment and complicated joints are not always as costly to make as they appear.

4. Stud welding can be used with advantage if strict supervision is maintained, allowing thinner flange sections to be used.

5. The design of fabrication components is of the utmost importance ; this alone can make fabrication by welding a success or failure in any company.

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Notes

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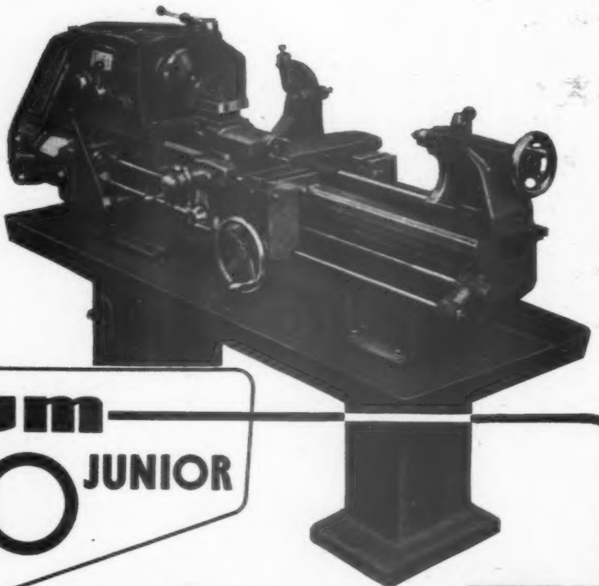

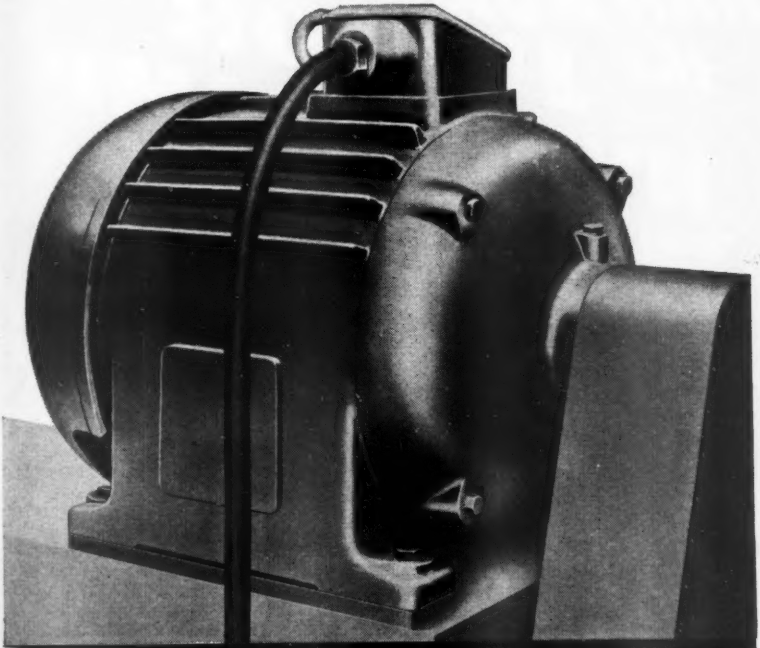

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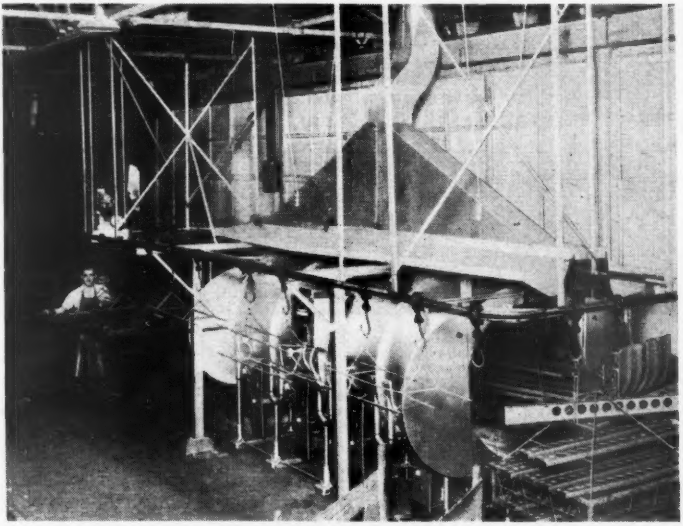

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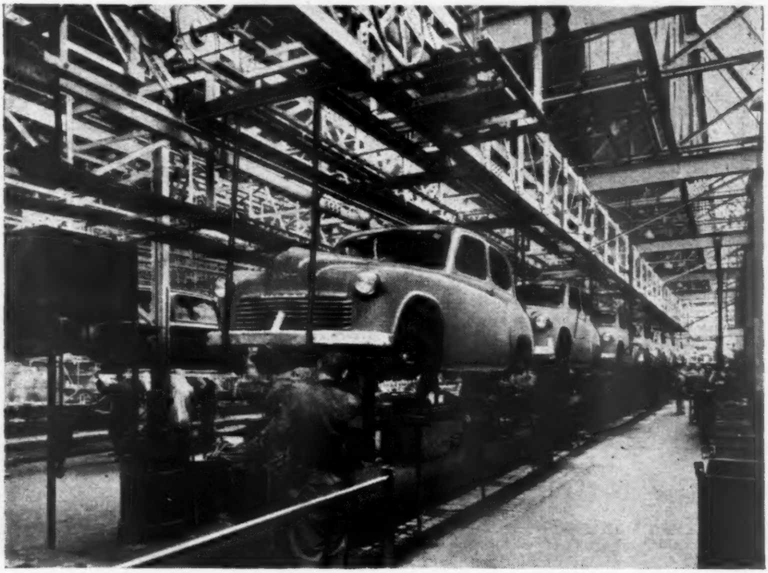

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